

**PARTIAL MELTING OF INDARCH (EH4) FROM 1000-1425°C: NEW INSIGHTS INTO IGNEOUS PROCESSES IN ENSTATITE METEORITES.** T. J. McCoy<sup>1</sup>, T. L. Dickinson<sup>2</sup>, and G. E. Lofgren<sup>3</sup>, <sup>1</sup>Department of Mineral Sciences, MRC 119, National Museum of Natural History, Smithsonian Institution, Washington DC 20560, USA, mnhs055@sivm.si.edu, <sup>2</sup>Physics Department, Catholic University of America, Washington DC 20064, USA, u1tld@lepvax.gsfc.nasa.gov or tdickins@nsf.gov, <sup>3</sup>Mail Code SN4, NASA/Johnson Space Center, Houston, TX 77058, USA, lofgren@snmail.jsc.nasa.gov.

**INTRODUCTION:** The differentiation of meteorite parent bodies by melting of chondritic precursors is a fundamental process in the formation of achondrites. These processes can be partially duplicated by laboratory experiments, which have shed significant new light on the melting of ordinary and carbonaceous chondrites [1,2]. Less progress has been made in understanding the melting of enstatite chondrites, in large part because of their highly reduced nature and difficulty reproducing these conditions experimentally. We report new experiments on the melting of the Indarch EH4 chondrite from 1000-1425°C under highly reducing conditions. We use these experiments to understand the physical and chemical processes occurring during differentiation of enstatite meteorite parent bodies.

**PREVIOUS WORK:** Preliminary experiments on the partial melting behavior of Indarch were reported by [3]. Noteworthy features in these experiments include: (1) the glass is virtually FeO-free, indicating that the intrinsic redox state of the samples was maintained, and S-rich, suggesting significant dissolution of sulfide in silicate melt (2) metal contains significant Si (4-12 wt %), with higher concentrations at increasing temperature [4] (3) metal/sulfide separated from silicate at lower degrees of partial melting than reported in high pressure experiments on a L3 chondrite [5]. Partial melting experiments on Indarch from 1250-1400°C [6] confirmed the incorporation of significant S in the melt and suggested that crystallization of the silicate melt can produce oldhamite observed in aubrites.

**EXPERIMENTAL:** Indarch, which we used as the starting composition for our experiments, consists of 72.6% silicates, 17.5% Fe-Ni metal, 7.3% troilite (FeS), 1.1% schreibersite ((Fe,Ni)<sub>3</sub>P), 1.0% niningerite ((Mg,Fe,Mn)S), 0.39% oldhamite (CaS), and trace amounts of daubreelite (FeCr<sub>2</sub>S<sub>4</sub>) and graphite [7].

The experimental technique used in the preliminary experiments was summarized in [3,4]. It was necessary to modify the earlier experimental technique slightly in order to maintain the desired  $fO_2$  at lower temperatures (1000-1300°C). In the current set of experiments, an alumina crucible containing Cr metal was sealed in the silica tube along with the graphite crucible containing the sample. Thus, the sample should stay at the Cr-Cr<sub>2</sub>O<sub>3</sub> buffer at all temperatures, which closely duplicates the intrinsic oxygen fugacity of enstatite chondrites. Samples were melted at 1425, 1400, 1300, 1200, 1100, and 1000°C. Charges discussed here were run for 20-24 hours. We found that this time range provided the appropriate balance between establishing chemical equilibrium within the charges and preventing volatilization of S, Na and K. Experiments run at 1000-

1100°C for 120 hours lacked sulfides, suggesting unacceptably high volatile loss. Relative homogeneity of phases within individual charges in our experiments suggests that chemical equilibrium was attained in the 20-24 hour run times.

**RESULTS:** We shall examine the textures, as well as the compositions of metal, sulfides and silicate melts for these new experiments.

*Textures:* Heating of the 1000°C charge was insufficient to produce a coherent charge and the final run product is a pellet of unconsolidated silicate, metal, and sulfide material. No silicate melting is observed. The 1100°C charge is also unconsolidated without silicate partial melting. Sulfides are absent and metal occurs as small, rounded particles, and as rims on larger silicate pieces, indicative of melting. The 1200°C charge is partially consolidated, with minor (<5%) silicate partial melting. The charge contains metal and two sulfide phases, commonly as independent grains, rather than intimate intergrowths of two or more phases. The 1300°C charge is coherent, but not compact, with silicate partial melting of ~10%. Metal and a single gray sulfide phase appear as distinct phases, not as intimate intergrowths. The 1400°C charge is coherent and compact, dominated by a small number of large metal-sulfide particles (several mm across). Significant (20%) silicate partial melt is present, but is probably microcrystalline and contains numerous small sulfide inclusions, which probably formed during quench. The 1425°C charge is almost texturally identical to the 1400°C charge, except that the large metal and troilite particles seem more concentrated around the edges. This could reflect random sampling or, perhaps, a greater surface tension effect manifested by slightly more silicate partial melting.

*Metal Compositions:* Metal compositions are given in Table 1. The 1100-1425°C charges contain between 5.0-8.4 wt.% Si, indicating that highly-reducing conditions were maintained during the run. Metal in the 1000°C charge is oxidized, with Si-free rims and 1-2 wt.% Si in the cores of the grains. The metal in all the charges is low in S and P, and contains 4-7% Ni. A few metal grains contain high and variable P abundances, reflecting preferential incorporation of schreibersite.

*Sulfide Compositions:* Sulfide compositions are given in Table 2. The 1000°C charge contains only one sulfide and it is very Cr-rich, suggesting that this charge was contaminated with some of the Cr-metal from the second crucible. No sulfides were present in the 1100°C charge, suggesting that there was sulfur volatilization in the silica tube. The 1200, 1400, and 1425°C charges contain two sulfides: one Fe-rich and the other Mg-rich (1200°C) or Mn-rich (1400 and 1425°C). The 1300°C charge contains

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only a Mg-rich sulfide. The Fe-sulfide contains approximately wt % levels of Ti, Cr, Mn and Ni, and only trace levels of Ca and Mg. The 1200 and 1300°C charges contain a Mg-rich sulfide with several wt% of Mn, Ca and Cr. The 1400 and 1425°C charges contain a Mn-rich sulfide, with wt % levels of Cr, Ca and Mg. In none of the charges were any relict sulfide grains observed.

**Silicate Compositions:** Silicate melt compositions are given in Table 3. Silicate melts are absent in the 1000 and 1100°C charges. At 1200°C, the silicate melt is enriched in SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, Na<sub>2</sub>O, and K<sub>2</sub>O relative to bulk Indarch [8], reflecting melting of plagioclase. This melt also contains 1.7 wt.% S, presumably combined with Ca in the melt [6]. With increasing temperature, the melt becomes systematically depleted in SiO<sub>2</sub>, Na<sub>2</sub>O and K<sub>2</sub>O and enriched in CaS and MgO. Al<sub>2</sub>O<sub>3</sub> does not vary substantially with temperature. The decreasing SiO<sub>2</sub> and increasing MgO likely reflect increased melting of enstatite. Increasing CaS reflects increases in both Ca and S in the melt, with S reaching 6.0 wt.% in our 1425°C charge. Decreasing Na<sub>2</sub>O and K<sub>2</sub>O reflects their preferential incorporation into the melt at low temperatures and increasing volatilization at high temperatures.

**DISCUSSION:** Several features of these recent experiments are notable. Perhaps most importantly, the addition of a metallic Cr buffer to our experimental technique allows us to reproduce extremely reducing oxygen fugacities at much lower temperatures than previously possible [3,6]. We still experience intermittent difficulties with oxidation and volatilization, probably due in part to a loss of integrity of the silica tube. Thus, some experiments will need to be replicated before firm conclusions can be made.

Where our new experiments overlap in temperature with those of [3], agreement in textures and metal, sulfide and silicate melt compositions is very good, suggesting that the graphite crucible alone produces appropriately reducing conditions at 1400-1425°C. Agreement with the silicate melt compositions of [6] is poorer. These differences do not appear to reflect a lack of equilibrium in either these experiments or those of [3], as suggested by [6]. Instead, we suggest that [6] may have not produced appropriately reducing conditions at all temperatures, as suggested by the low S and high FeO contents of the silicate melts in some of their experiments.

Several implications can also be gleaned from this new data. In agreement with [3,6], we find that significant S can be accommodated in the silicate melt at reducing conditions. As [6] pointed out, this S likely combines with Ca and Mg in the silicate melt and can crystallize oldhamite upon cooling. Our new data, however, allows us to examine the melting of sulfides and their distribution between silicate and sulfide melts at lower temperatures. These results suggest that incorporation of S in the silicate melt becomes more efficient at higher temperatures, where significant Ca, Mg and S are found in the silicate melt, while one of the sulfide melts is Mn-rich. In contrast, at low temperatures, Mg and Ca are primarily observed in a sulfide melt.

An important conclusion of this work is that at temperatures as low as 1200°C, no relict sulfides are observed and Ca, Mg, Mn and Cr are incorporated into either a sulfide or silicate melt. We find that oldhamite is not a stable phase at temperatures down to 1200°C where silicate melt exists and could not survive igneous processing on the aubrite parent body, in agreement with [6] and contrary to the suggestion of [9].

Charge	Temp (°C)	Time (Hr)	Si	Fe	S	P	Ni	Total
TD 270	1000	24	1.1	90.85	0.07	0.47	6.88	99.37
TD 265	1100	24	5.54	87.19	0.05	0.58	5.62	98.98
TD 261	1200	24	4.96	88.01	0.16	0.25	5.73	99.11
TD 268	1300	24	8.42	85.78	0.08	0.45	4.85	99.58
TD 269	1400	24	4.9	87.96	0.08	0.36	5.91	99.21
TD 262	1425	20	5.75	87.22	0.19	0.39	6.38	99.93

**REFERENCES:** [1] Jurewicz et al. (1993) GCA 57, 2123-2139. [2] Jurewicz et al. (1995) GCA 59, 391-408. [3] Dickinson and Lofgren (1992) LPSC XXIII, 307-308. [4] Dickinson et al. (1992) LPSC XXIII, 309-310. [5] Takahashi (1983) Proc. 8th Symp. Antarctic Met. 168-180. [6] Fogel et al. (1996) LPSC XXVII, 371-372. [7] Keil (1968) JGR 73, 6945-6976. [8] Wiik (1956) GCA 9, 279-289. [9] Lodders (1996) MAPS 31, 749-766.

Charge	S	Fe	Ti	Cr	Mn	Ca	Mg	Ni	Total
Fe-rich sulfides									
TD-270	None								
TD-265	None								
TD-261	37.1	57.2	0.44	2.69	0.68	0.03	0.11	1.45	99.7
TD-268	None								
TD-269	37.5	54.4	0.77	4.38	1.32	0.01	0.09	1.14	99.61
TD-262	37	57.5	0.62	2.53	1.37	0.02	0.04	0.81	99.89
Other sulfides									
TD-270	39.9	33.8	0.02	24.7	0.81	0.01	0	0.25	99.49
TD-265	None								
TD-261	43.4	25.6	0.17	2.23	7.68	9.23	11.9	0.03	100.24
TD-268	46.6	17.6	0.9	3.68	7.21	4.48	19.5	0.03	100
TD-269	38.6	37.2	0.37	4.34	14.5	1.41	2.84	0.31	99.57
TD-262	37.9	41.4	0.38	3.22	14.2	0.93	1.71	0.35	100.09

Charge	Temp.	Time	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	MnO	FeO	CaO	CaS	MgO	MgS	Na <sub>2</sub> O	K <sub>2</sub> O	Cr <sub>2</sub> O <sub>3</sub>	Sum	Total S
TD-270	1000	24	No Silicate Melt Present													
TD-265	1100	24	No Silicate Melt Present													
TD-261	1200	24	69.16	0.00	13.52	0.01	0.76	3.86	3.73	7.64	0	2.62	0.45	0.01	101.76	1.66
TD-268	1300	24	59.06	0.12	13.74	0.05	0.53	0.47	11.84	16.75	0	0.14	0.10	0.05	102.85	5.26
TD-269	1400	24	52.49	0.15	14.19	0.12	0.35	2.50	12.68	19.16	0	0.03	0.02	0.12	101.81	5.63
TD-262	1425	20	53.68	0.24	13.92	0.16	0.34	1.42	13.53	18.92	0	0.02	0.03	0.06	102.32	6.01
Average Aubrite			58.6	0.05	0.95	0.05	0.07	0.92		37.7		0.49	0.03	0.03		
Indarch Silicates			61.82	0.11	2.54	0.44	0	1.67		30.65		1.77	0.19	0.82		